NGU REPORT
2020.020

“Shaken not stirred”: Mosaic sand – a semi-liquefaction phenomenon originating from strong earthquakes

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Mosaic sand assumed induced by strong earthquake in a water-saturated, primarily deposited sub-littoral layered fine- to medium-grained sand. Photograph from the Halsa mosaic sand field, North Norway.

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Summary:

The formation of *mosaic sand*, here as exemplified from a 0.23 km^2 sand field at the coast of Nordland County in Northern Norway, is thought to be related to earthquake induced shaking, re-mobilization and partial (semi-) liquefaction of water-saturated, stratified fine and medium sand. It is therefore a part of the broad class of sediments with seismically induced deformations, known as *seismites*. The process associated with the formation of mosaic sand may best be described as 'shaken, not stirred', because the individual parts of stratified sands are apparently not totally removed from their original position. The layers are rather broken, fragmented in pieces or ball-like structures, which are deformed, partly rotated and then settled in a complex mosaic mixture. It may also appear just as a cluster of load casts. The structure developed resembles those of a dense conglomerate, a cluster of pseudo-nodules, or as pudding balls (armored sediment balls) cemented by sand.

The mosaic sand formations where first observed three decades ago at the coast of Trøndelag County in Mid-Norway and are so far recorded at 19–20 sites in Mid- and Northern Norway. These are all thought to have been, primarily before shaking and deformation, a series of water-lain, shallow marine alternating fine to medium sand layers. Water-saturation during formation likely indicates an environment close to sea-level, and the sites' elevation may thus, where high-resolution sea-level records are available, yield a relative dating method for the associated earthquakes. A modifying factor for these estimations may be a possible abrupt temporary rise of groundwater level during earthquake, especially at locations close to fault or fracture zones in bedrock.

An implication of occurrences of mosaic sand is that it may record periods of relatively high postglacial seismicity. For example, the presented mosaic sand at Halsa in Nordland is located, together with several similar sites, in an area with recorded active seismicity today, and future earthquakes of relatively high magnitude in this area should therefore be expected.

Keywords: Earthquakes	Liquefaction	Seismicity
Holocene sea levels	Sediment deformation	Seismites
Water saturation	Abrupt groundwater rise	

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FIGURES

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Shaken, not stirred: Mosaic sand – a semi-liquefaction phenomenon originating from strong earthquakes

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Introduction

The formation of mosaic sand, or ball and mosaic sand, is thought to be triggered by earthquake shaking, and as such it is a type of seismite (Lagerbäck 1990), with re-mobilization and partial (semi-) liquefaction of water-saturated, layered fine and medium sand. The process may best be described as 'shaken, not stirred', because the individual parts of the originally layered sand are apparently not always totally removed from their original position. The layers are just broken, fragmented in pieces or balls, which are deformed, set in motion, partly rotated and then settled, during water escape, in a complex mosaic mixture. In some parts it may appear just as a cluster of load casts. The structure developed resembles those of a dense conglomerate, or as pudding balls (armored sediment balls) cemented by sand.

In this report we will present a series of photographs from the record of sediments in a 0.23 km^2 sand field, the Halsa mosaic sand field, at the coast of Nordland County in Northern Norway (Figs. 1–4), and from some other sites in coastal Norway hosting structures described as "ball and mosaic sand" or similar structures, all assumed to be formed triggered by earthquake. Other deformational mechanisms, such as landslides, rapid sediment supply with gravity flow, glaciotectonics, cryoturbation and other periglacial processes, etc., are considered much less likely, or even not likely in these cases.

The mosaic sand formation as presented here, and as also recorded at 19 other sites in Middle and Northern Norway (Figs. 1–2), is thought to have been primarily a series of water-lain alternating fine to medium sand layers of dark heavy minerals and lighter minerals. The shaking of the water-saturated sand has then supposedly broken the layers and fractionated these in lighter 1-4 cm diameter sand balls or fragments, armored with darker heavy mineral sand. In some parts, where the layers of lighter minerals supposedly originally where thinner than the layers of dark heavy minerals, the sand layer fragments or balls after shaking may appear with a darker core and lighter outer parts. However, this situation seems to be less frequent occurring at the sand sites observed so far.

The fragmented parts of the unit have been floating and acted together as in a continuous body, partly flowed and moved as a liquid (liquefaction), before it finally has settled and ended with the structures as in the picture (Fig. 1). Typically, it is often also present more plastic deformation structures and gravitational, liquefaction "ball and pillow" like forms and load casts in more fine-grained, dense and more liquefied sediments below ball or mosaic sand units.

Ball and mosaic sand units have been recorded as a part of general Quaternary mapping during the last three decades in the coastal area of Middle and Northern Norway. The sites are located at various elevations a.s.l., and the mosaic sands have been made by deformation of originally layered shallow marine sands deposited during Holocene. These special structures are thought to derive from strong earthquakes, since a magnitude of at least M = 4.5–5 is required for the formation of seismites with liquefaction features (van Loon et al. 2016), here with shaking of water-saturated, originally layered fine to medium sand. Most of these sites represent original deposition shortly after the last deglaciation, and around the Tapes transgression (c. 6–7 kyr BP), and subsequent deformation, which may indicate increased seismic instability of the Earth crust during these time periods.

The lowest laying, and therefore supposedly youngest mosaic sand sites, perhaps as young as 2–3 kyr have been recorded in an area with active seismicity today (Fig. 5). The location is not far from the strongest modern earthquake recorded in Nordland County, magnitude 5.8 in 1819 A.D. at Lurøy (Figs. 3–5).

Figure 1. Ball and mosaic sand structures in shallow marine sand at a location c. 60–70 m a.s.l. at Halsa, north of the Arctic circle, Nordland County, northern Norway. After Olsen 2018.

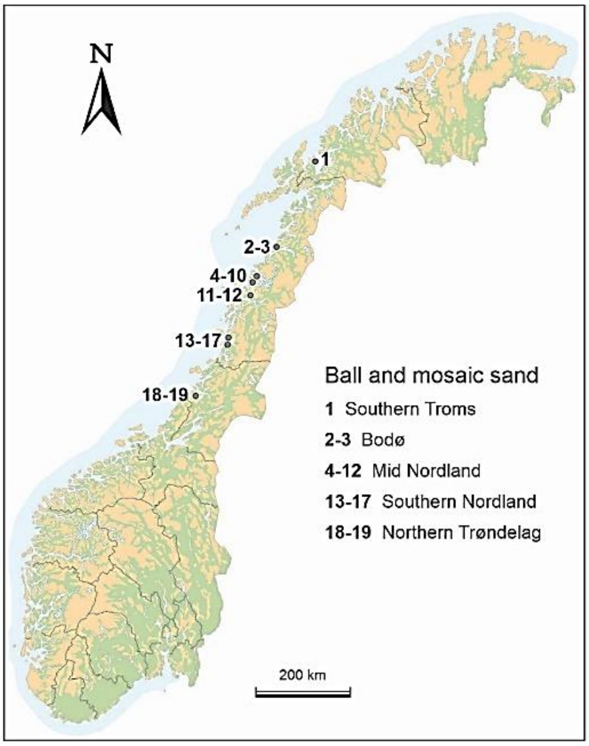


Figure 2. Recorded sites with mosaic sand units along the coast in Northern and Central Norway, 1990–2019. The presented sites Halsa and Klubbsteinen are represented as locality nos. 4 and 19, respectively. Site no. 20, recorded last year, is from the same area as indicated for nos. 4–10.

The Halsa mosaic sand, Nordland County

In the following text and illustrations we will describe one of the mosaic sand sites, and try to show that earthquake is the most plausible cause that could possibly lead to the formation of thick and extensive units of semi-liquefied ball and mosaic sand, which is related to but clearly different from the well-known “ball and pillow” structures also made by gravitational, liquefaction processes. The latter is often presented in thinner units above or below mosaic sand units, where dense parts of the sediments have been sinking in the surrounding sediments, in parts making nice load casts, in a liquefaction process. More plastically formed deformations, both vertically and horizontally extended are also commonly found both in over- and underlying mosaic sand units, and especially in more fine-grained units underlying mosaic sand.

Several meters thick, layered shallow marine sands deposited during the last deglaciation and early Holocene in an area of size at least 650 x 350 m^2, i.e. > 0.2 km^2 (Figs. 3 and 4) are deformed and restructured to give a mosaic or conglomeratic appearance. The location is close to an area, indicated with red arrow in Fig. 3, which is seismically active today (Fig. 5; and Janutyte et al. 2017).

Figure 3. Location of a large field (encircled) 50–70 m a.s.l. (Fig. 4), with thick layered shallow marine sands, subsequently deformed with the outcome described as ball and mosaic sand. Location of a close-lying seismically active zone today is indicated with red arrow.

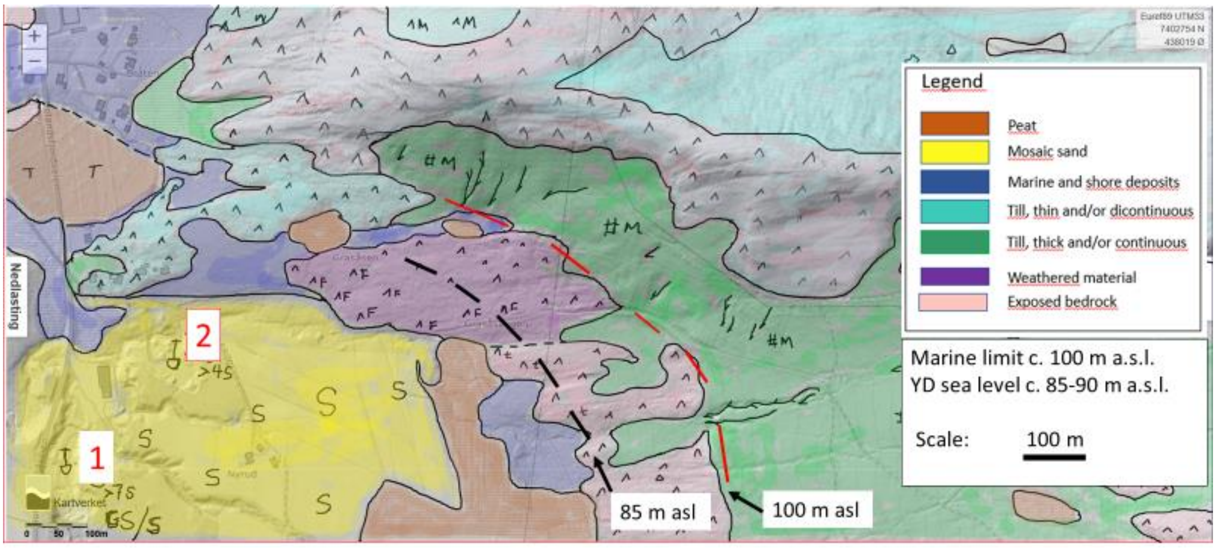


Figure 4. Halsa sand field (yellow colour) c. 50–70 m a.s.l., size: 650x350 m^2. 1= old sand pit, and 2= new sand pit. Late-/postglacial marine limit is c. 100 m a.s.l. in this area.

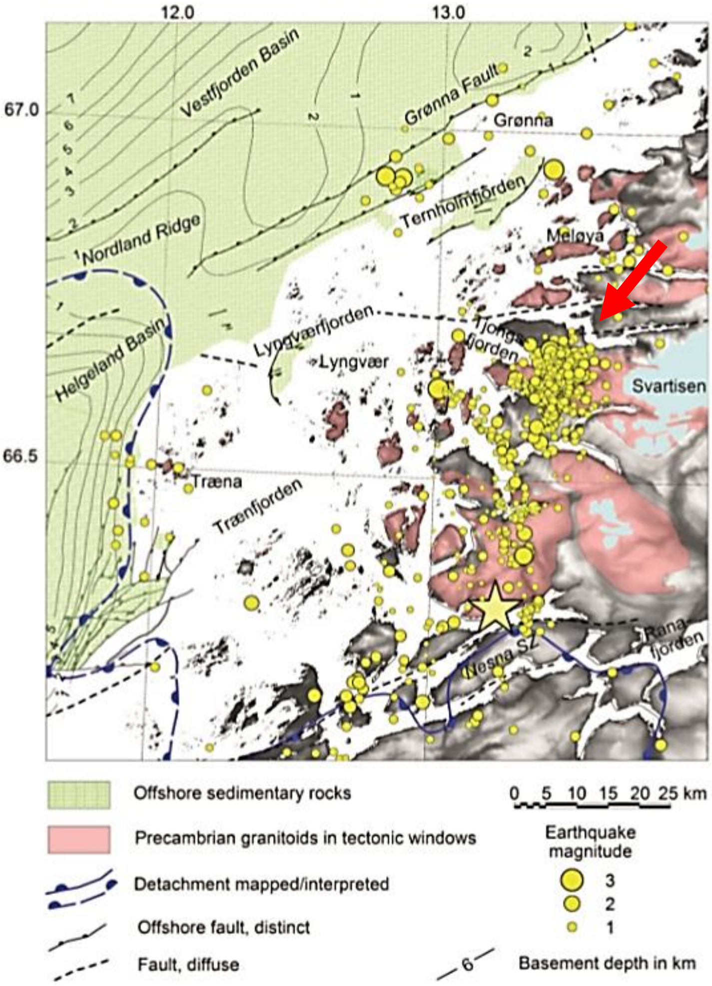


Figure 5. Seismic activities today in the area west of the Svartisen glacier in Mid Nordland. The location of the Halsa mosaic sand field is indicated with a red arrow. Yellow circles indicate earthquake and earthquake magnitudes recorded in recent years. The yellow star indicates the assumed epicenter of the historic 5.8 magnitude earthquake in the Lurøy area in 1819 A.D. For further details, see Janutyte et al. (2017).

Figure 6. A 6m-high section in the southern part of the old sand pit (see Fig. 4). Terrace is sloping to a crossing creek to the right.

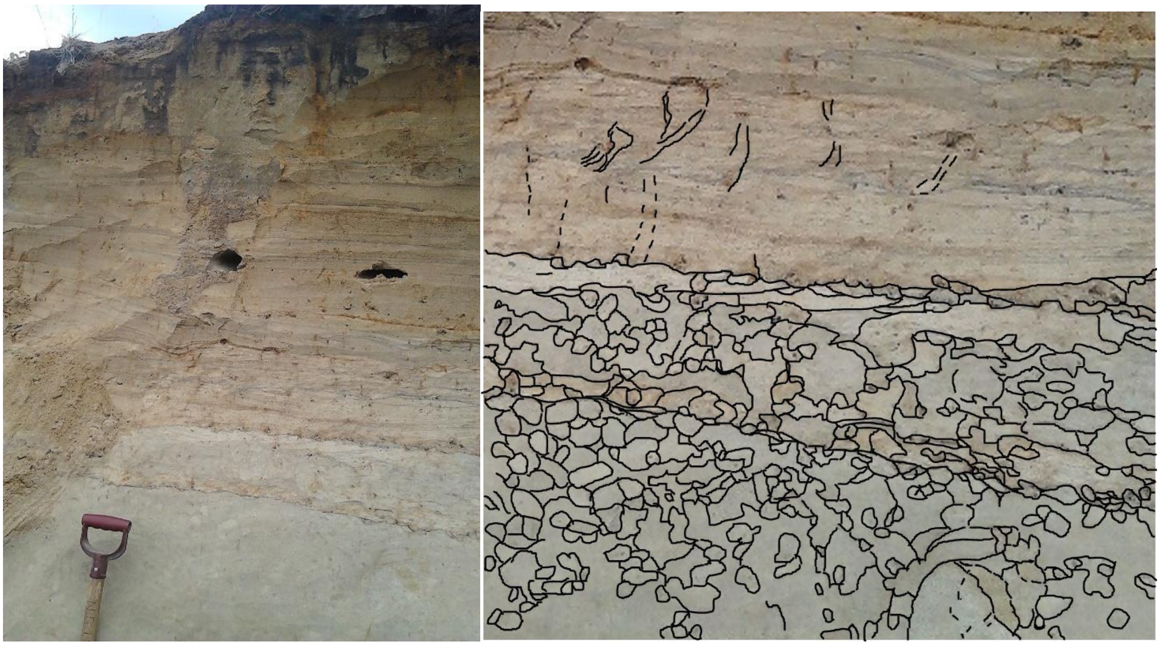


Figure 7. Close-ups of a section in the upper left of the sand wall in Fig. 6. Undeformed plan laminated, massive and riffled coarse, medium and fine fluvio-marine sand from terrace surface at c. 51 m a.s.l. and downwards to 0.8 m depth (middle of image). Below this level all units, which is dominated by fine and medium shallow marine sands are deformed. Image to the right: Close-up of the lower half of the left image. Main mosaic structures from the deformed units are indicated with hand drawn lines, and some possible water escape structures in the layered sand directly overlying the mosaic sand are indicated (broken lines), as well.

It is a transition from plastically formed structures, with folding and lateral stretched features, to more ball and mosaic structures downwards in the deformed sediments (Fig. 7).

Figure 8. Additional sections from old sand pit wall (Fig.6). Left: Undeformed plan laminated, massive and riffled coarse, medium and fine fluvio-marine sand from terrace surface at c. 51 m a.s.l. and downwards to a thin brown oxidized horizon (middle of image) 0.8m below surface. Deformed shallow marine medium and fine sand units below this horizon. Right: Knife in same position as in the left image, and deformation structures change from plastic forms, partly folded and stretched laterally to more ball and mosaic forms downwards.

Below the edge of the knife (Fig. 8, right image) a typical ball and mosaic sand occur in a thick and extensive unit that may be followed in the upper parts of the sections everywhere in the Halsa sand field, except for some 10–20 m adjacent to the present creek that crosses the southern part of the field. In the latter zone the undeformed fluvio-marine sand unit seen in the upper part of Fig. 7, and in the left image of Fig. 8, is overlying the mosaic sand unit. The deformed sand unit just above the mosaic sand includes also gravitationally formed load casts and pseudo nodules, as illustrated in Fig. 9.

Further illustrations from the Halsa mosaic sand field, including simplified stratigraphic logs, follow in Figs. 10–17, with complementary images also added in Appendix as well (Figs. A1–A3).

Figure 9. Gravitational load casts, pseudo nodules, folding and other disruptions in deformed sand between mosaic sand zones in the sediment sequence represented in the old sand pit (Fig. 6).

Figure 10. Details from transition between plastic deformation and underlying mosaic sand, from the upper part of the sand sections in the old sand pit at the Halsa mosaic sand field.

Simplified stratigraphic logs plotted on a profile across the the Halsa mosaic sand field illustrate the extent of the mosaic sand, which is reaching more than 600 m in a W–E direction (Figs. 11–13). These data also illustrate the thickness of the mosaic sand and the context with abundance of various deformations represented in the underlying silty-sandy sediments.

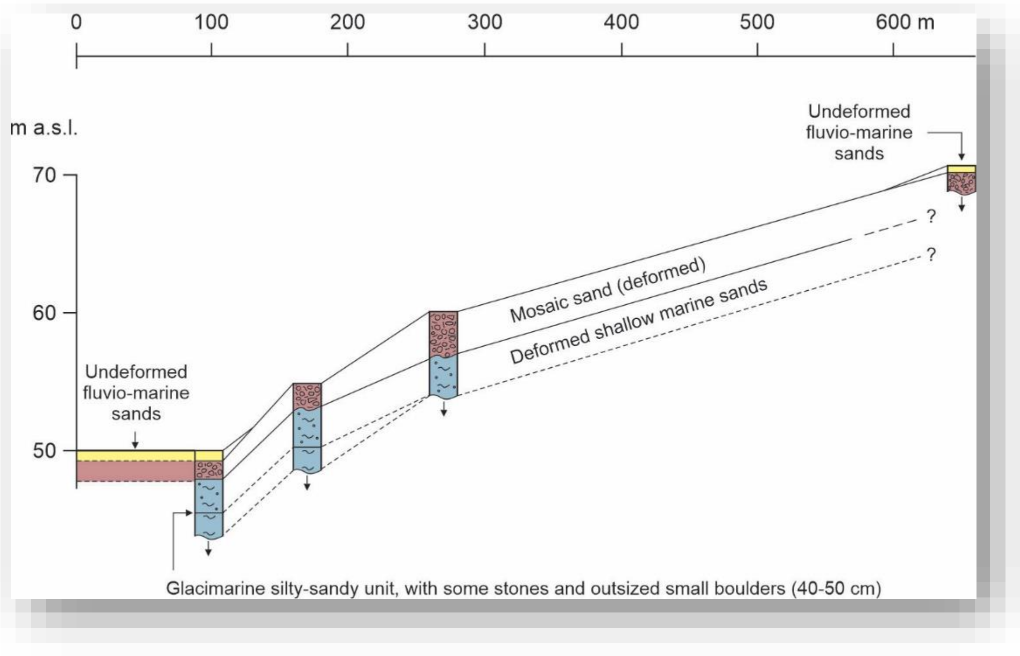


Figure 11. Simplified logs along a W-E profile across the Halsa mosaic sand field (for location, see Fig. 4).

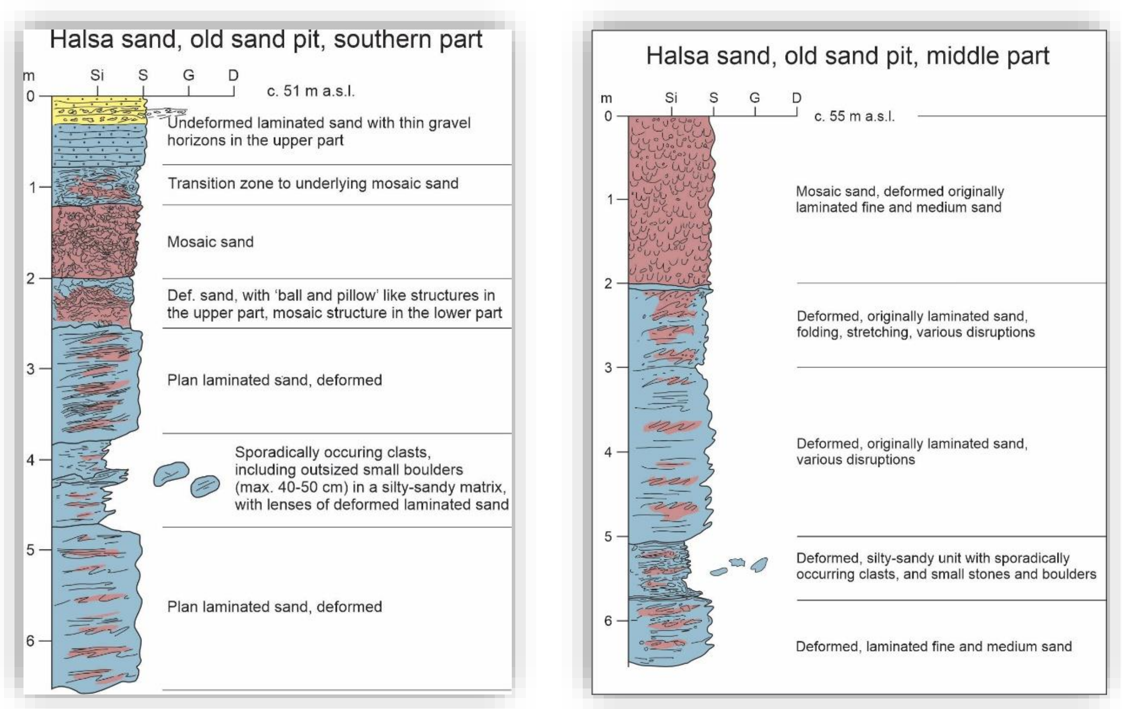


Figure 12. Left: Simplified log from the western part of the profile shown in Fig. 11. Right: Simplified log from the old sand pit in the western part of the profile shown in Fig. 11.

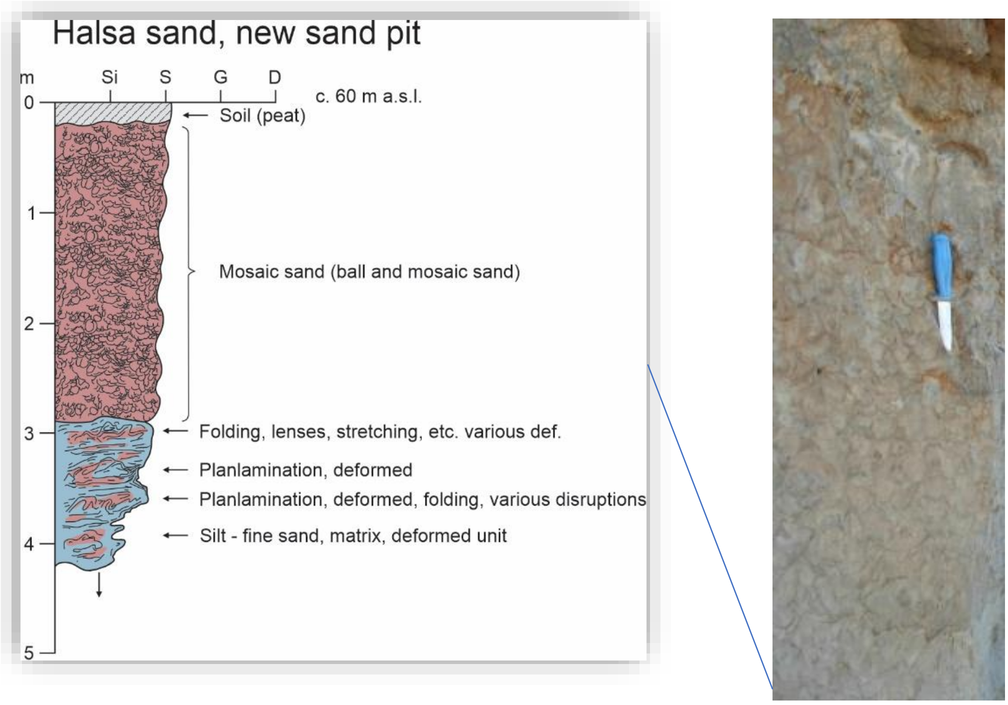


Figure 13. Left: Simplified log from the new sand pit at Halsa mosaic sand field (middle part of profile in Fig. 11). Right: Photograph from the mosaic sand unit indicated in the log (see enlarged images in Figs. 1 and 14).

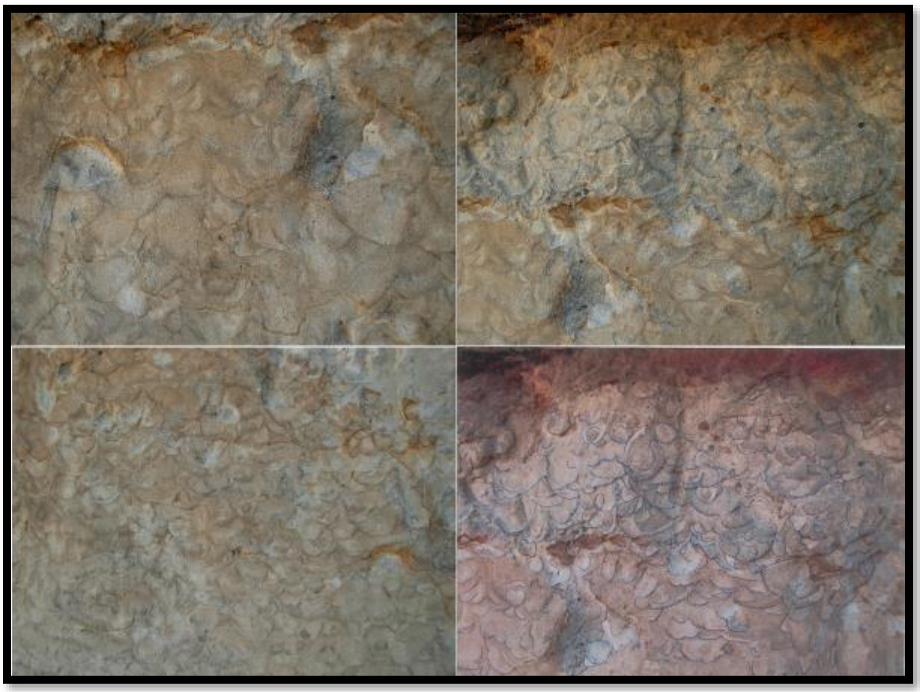


Figure 14. Pictures of the mosaic sand from the new sand pit (c. 60 m a.s.l.) in the upper sediment unit in Fig. 13. Main mosaic structures are indicated with hand-drawn lines in the lower right picture. Scale is indicated in Fig. 1.

Various plastically formed, elongated deformational structures, including folds, occur in silt and sand underlying the mosaic sand zones in sections from the new sand pit at Halsa (Figs. 15–17). The thickness of the deformed sediments is up to more than 6 m in parts of the mosaic sand field, e.g. Fig. 12 (log to the right), where just the lowermost meter seems to be deformed, most likely because of ice-drop boulders included, by glaciotectonics or iceberg impact and probably not be earthquake.

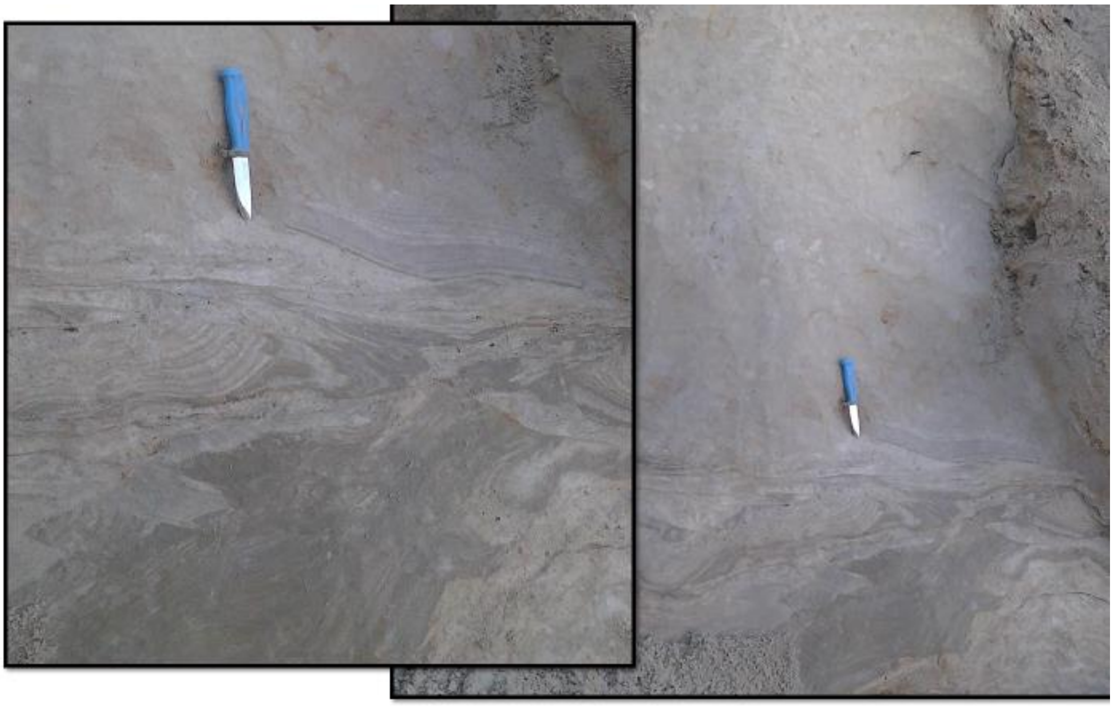


Figure 15. Transition between mosaic sand and underlying deformed sandy and silty sandy sediments. Knife edge is at the boundary between the sediment units.

Figure 16. Pictures of deformed layered sand in the lower part of lower sediment units indicated in the log in Fig. 13, c. 57 m a.s.l.

Figure 17. Deformed layered sand at the base of the section in the new gravel pit, 55 m a.s.l., Fig. 13.

Additional sites with mosaic sand in the vicinity of the Halsa mosaic sand field

In a 2x2 km^2 area a few km SW of the Halsa mosaic sand field four or five additional sites with mosaic sand are recorded. These are located at different elevations spread from 15 m to 80–100 m a.s.l. (Fig. 24). The sites at 15 m (Fig. 18), 50–70 m (Fig. 19), 80 m (Fig. 20) and 90 m a.s.l. (Fig. 21) are clearly of the mosaic sand category, with the most likely cause of deformation being strong earthquake. The fifth site, at c. 100 m a.s.l. (Fig. 22), is different hosting a more variable kind of deformations, possibly mainly derived from glaciotectonics since it is situated just outside the downstream end of a drumlin from the last deglaciation there (Fig. 24). However, the close location to the 80–90 m a.s.l. mosaic sand sites suggests that some of the deformations at 100 m a.s.l. may derive from earthquake disruptions.

Figure 18. Mosaic sand at Esvikelva, 15 m a.s.l. in the Kila area (Fig. 24). Water escape structures in close-up to the right.

Figure 19. Mosaic sand at 50 m a.s.l. (Fig. 24) to the right and lower left, and from 70 m a.s.l. in the same area, to the left, upper picture.

Figure 20. Mosaic sand from 80 m a.s.l. (Fig. 24).

Figure 21. Mosaic sand from 80–90 m a.s.l. (Fig. 24).

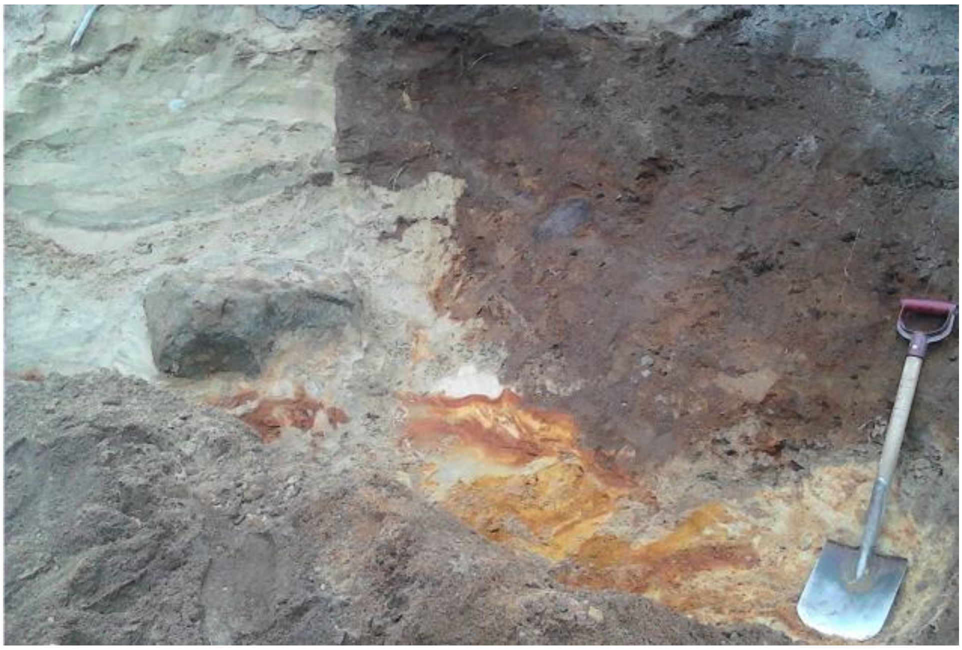


Figure 22. Deformations in glaciofluvial sand (light gray and red-orange oxidized area) with some boulders, underlying deformed glaciofluvial gravel (dark area, upper right), c. 100 m a.s.l. (Fig. 24). Main deformations probably formed during glaciotectonic movement, some deformations in the sand may however derive from earthquake.

Just a few km east of the map shown in Fig. 24, mosaic sand is recorded c. 15 m a.s.l. (Fig. 23) and thus providing an additional data-point to the drawing shown in Fig. 25 with elevation of mosaic sand sites plotted with estimated time based on a general shore displacement curve from the area.

Figure 23. Mosaic sand at Reppen c. 15 m a.s.l. a few km east of the map area shown in Fig. 24.

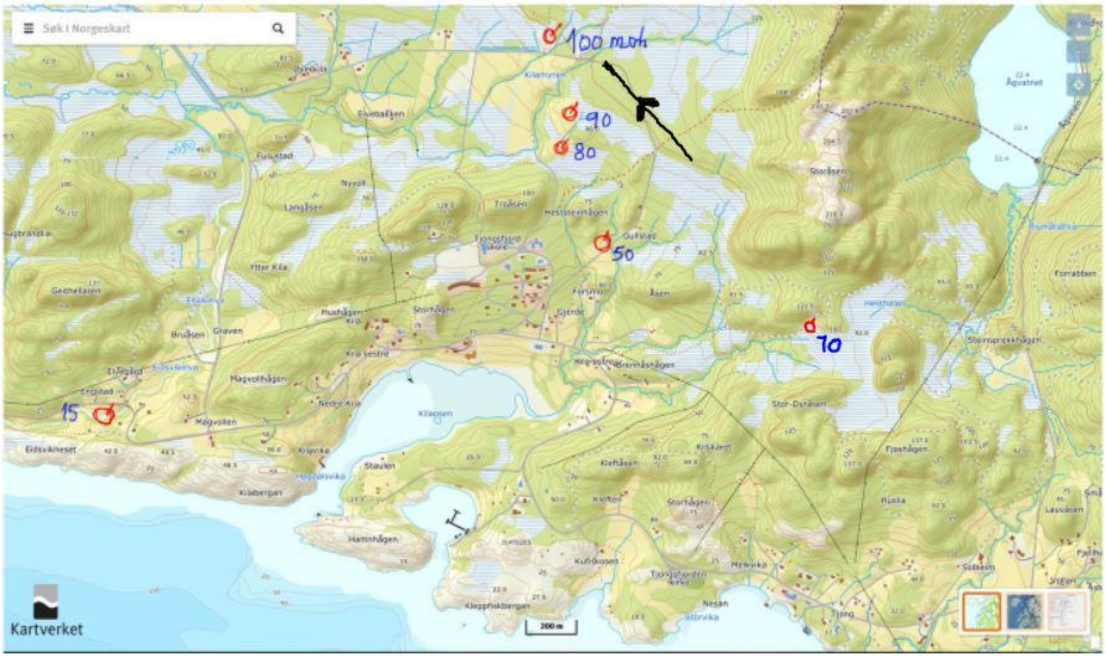


Figure 24. Mosaic sand sites in the Kila area, in the vicinity of the Halsa mosaic sand field, all situated in a region which is seismically active today (see Fig. 5). The elevation of the mosaic sand varies from 15 m to 80 m a.s.l., and possibly up to 100 m a.s.l. Undeformed littoral sand on top of each site at various elevations indicate formation of mosaic sand at different age from site to site. Due to the requirement of water-saturation during formation these elevations therefore indicate formation during various sea-levels and consequently during different times in an area with general sea-level regression during most of the Holocene. Drumlin-like ridge from Older Dryas ice advance is indicated with arrow.

Water-saturation during formation is the crucial factor which makes it possible to connect mosaic sand site elevations to associated sea-levels in this fjord landscape. Plotting mosaic sand sites' elevations on a shore displacement curve provide therefore a possibility to estimate the age of the formation of each mosaic sand occurrence, and therefore also the estimated age of each associated earthquake.

A moderating factor for estimation of the water-level during associated strong earthquake is that the local groundwater horizon is often raised considerably during shaking of the ground, particularly in fault areas. This was observed, e.g., as groundwater poured out on the ground adjacent to the Stuoragurra fault on Finnmarksvidda, during or shortly after earthquakes of magnitude 3 there in 1996 A.D. (Dehls et al. 2000). This factor may reduce the estimate of water-level, or sea-level in these fjord landscape settings, possibly by a meter or two, but probably not by several meters. In spite of such a small correction, this factor should be considered although no distinct fault zones are recorded in the Halsa mosaic sand field area and surroundings.

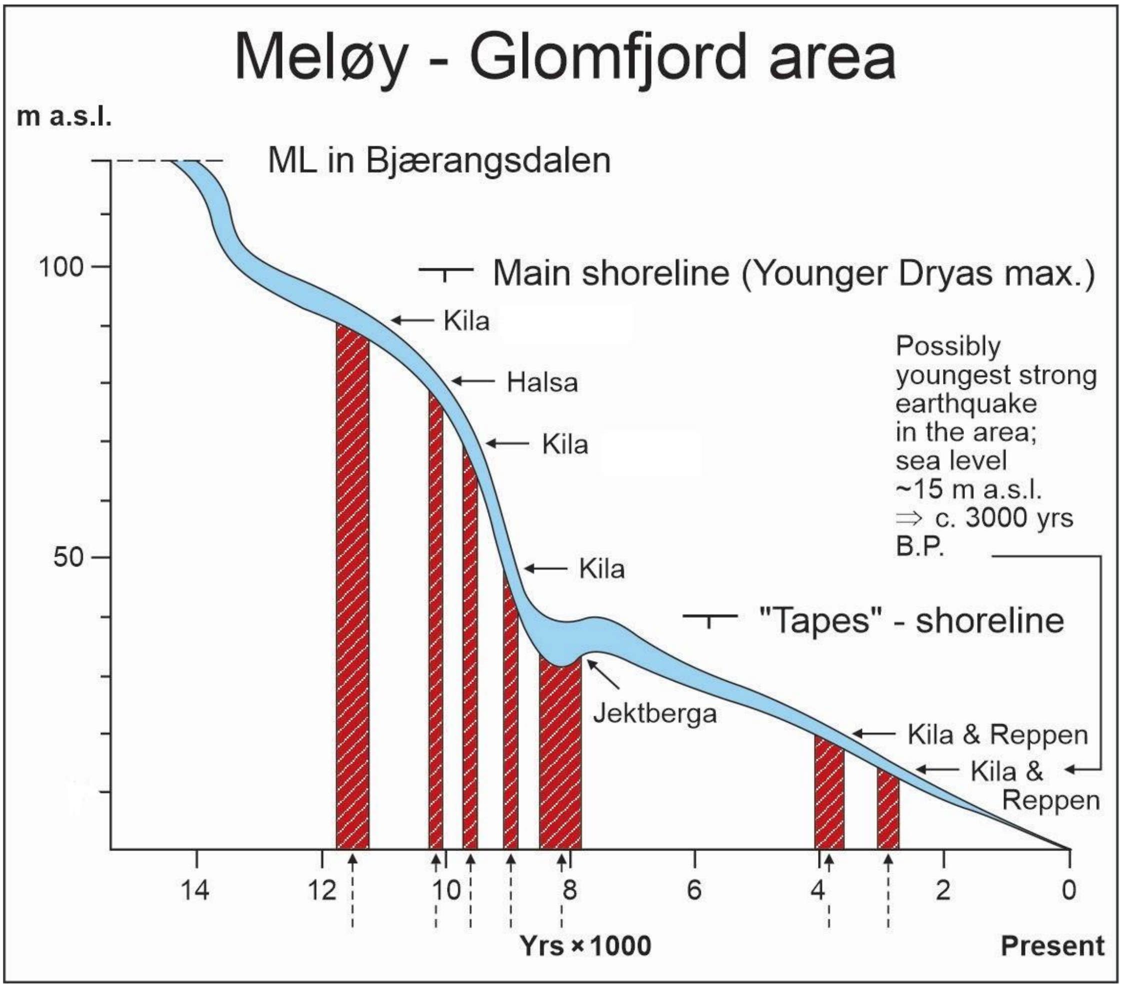


Figure 25. Position in m a.s.l. for the various mosaic sand sites in the vicinity of the Halsa mosaic sand field plotted on a general shore displacement curve from the area, with resulting inferred earthquake and formation intervals for the mosaic sands (red shading) indicated, as well. This is just an example of a method for age estimation, which may be considerably improved by using a more precise, local shore displacement curve rather than just a generalized one representing a wider area as in this case.

The Klubbsteinen mosaic sand, Trøndelag County

The first record of “ball and mosaic” sand from Norway was done during general quaternary mapping by the Geological Survey of Norway around 1990 A.D. in the coastal area of Mid Norway (Olsen and Sveian, 1994), and the first site described was from Klubbsteinen in the northern Trøndelag area (Fig. 26).

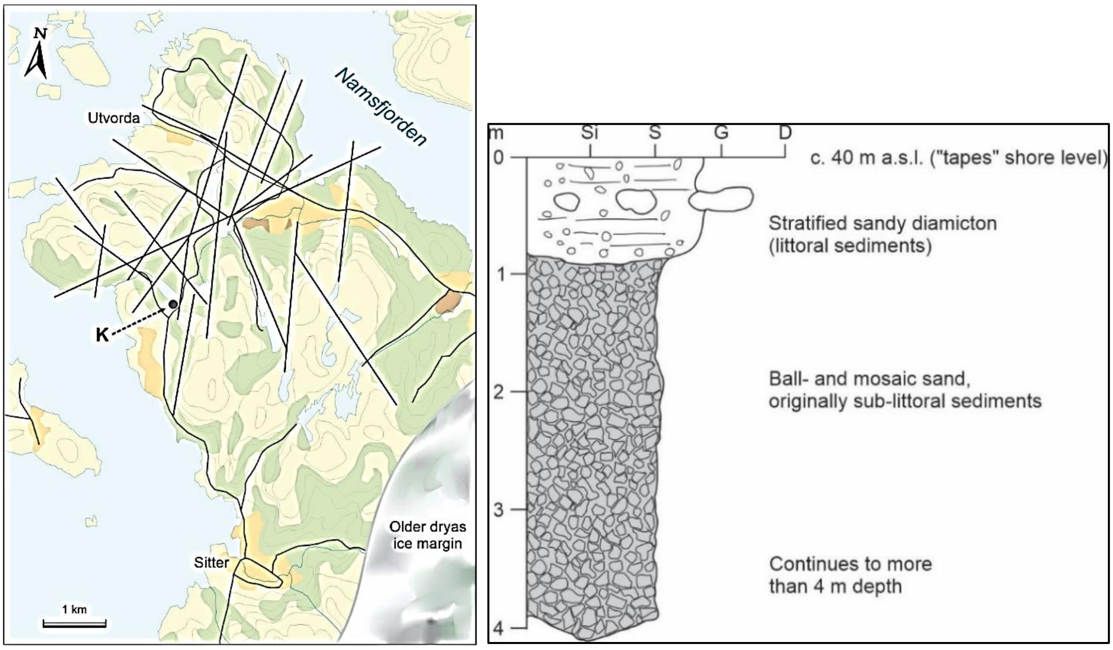


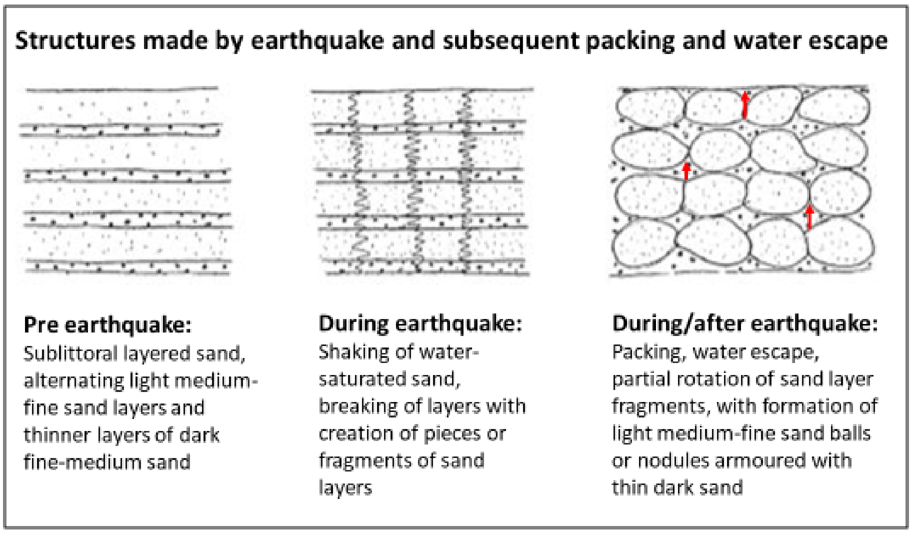
Figure 26. Left: Location of the Klubbsteinen (K) mosaic sand site in the northern Trøndelag area (also Fig. 2). Faults or elongated fractures in bedrock which may occasionally have hosted increased seismic activity during time are indicated (black straight lines). Right: Simplified log from the Klubbsteinen mosaic sand.

Figure 27. Ball and mosaic sand c. 38 m a.s.l. from Klubbsteinen, northern Trøndelag County. Left: Photograph by H. Sveian 1991. Right: Mosaic structure accentuated by hand drawing.

Figure 28. Pseudo nodules in earthquake induced deformation in sandy, originally glaciofluvial sediments deposited below marine limit in the area close to the postglacial Lansjärv fault in northern Sweden (from Lagerbäck and Sundh, 2008). These structures seem to be almost similar as some of the structures developed in the most water-saturated parts of the mosaic sand, e.g., in the Halsa mosaic sand field. These structures deviate more from the mosaic sand at Klubbsteinen where water saturation during deformation may have been a little less than 100%, which is indicated by the more angular sand layer fragments represented (Fig. 27).

Formation of ball and mosaic sand

A model attempting to describe the formation of ball and mosaic sand is shown in Fig. 29.



Structures made by earthquake and subsequent packing and water escape

Pre earthquake: Sublittoral layered sand, alternating light medium-fine sand layers and thinner layers of dark fine-medium sand

During earthquake: Shaking of water-saturated sand, breaking of layers with creation of pieces or fragments of sand layers

During/after earthquake: Packing, water escape, partial rotation of sand layer fragments, with formation of light medium-fine sand balls or nodules armoured with thin dark sand

Figure 29. Model attempting to describe the formation of ball and mosaic sand. Water escape during and after earthquake is indicated with red arrows.

The model starts with originally deposited shallow marine fine to medium sand with alternating light (light minerals) and dark (heavy minerals) layers. It continues with earthquake influence, including breaking of sand layers in fragments of various size and forms, water escape, partial rotation of fragments, armoring of some of the balls or fragments, and final sinking and settling of all parts of the disturbed sand to the end product is achieved: *the ball and mosaic sand*. With full water saturation during earthquake and deformation the individual sand layer fragments are supposed to be more rounded, teardrop or ball-like, as at the Halsa mosaic sand (Fig. 1), and even more drop-like as from Lansjärv postglacial fault area, northern Sweden (Fig. 28), whereas less complete water saturation may give more angular fragments and structures, as at the Klubbsteinen mosaic sand site (Fig. 27).

Additional pictures from the Halsa mosaic sand field and from mosaic sand further south along the coast in Nordland County are included in Appendix. These may all work as examples of various deformation structures in mosaic sand, deviations from or similarities to the model end-product, to the ball and drop like parts of Halsa mosaic sand (Fig. 1), or to the Klubbsteinen mosaic sand (Fig. 27). Deformation in soft sediments like sand, silt and clay may have its origin in various processes, e.g. from landslides, rock avalanche impact, glacial impact, extremely rapid sediment support with gravity flow, earthquake, etc. In thin sedimentary units, just a few dm thick, any of these processes may possibly give ball and mosaic structures in water-saturated sand. It is much less likely to get m-thick, relatively homogenous mosaic sand from other processes than earthquake. We have not seen by ourselves or reported from other areas any examples that deviate from the hypothesis that earthquake is the main triggering mechanism of formation of mosaic sand in thick sand units.

Discussion of alternative deformation mechanisms as triggers for mosaic sand formation

Our main hypothesis for the cause and triggering mechanism for mosaic sand formation is earthquake, but other deformational mechanisms are considered possible at some of the observed sites. This is indicated in Table 1, where all 19 former and 2 new recorded mosaic sand sites are listed, and where other deformational mechanisms in addition to earthquake are considered possible for 12 of the 21 sites. In 7 of these 12 sites we cannot rule out the possibility that other mechanisms than earthquake may have caused the deformation of the sands, mainly because the mosaic sand zones are thin, just a few dm thick and constitute just a minor part of the deformations of the sediments at these sites. In these cases, more plastically, elongated structures with folds often dominate the deformations in underlying sands or finer soft sediments. This indicates more horizonal or lateral impact than that associated with mosaic sand, which indicate more vertical distortion and disruption. Where the mosaic sand zones are thick and dominate the overall deformations, we think that earthquake is the more likely cause of deformation, and vice versa, where other deformational structures strongly dominate, then other mechanisms than earthquake may more likely have significantly influenced the deformations. The new site at Grinder (no. 21) is one of these (Fig. 30), where glaciotectonics are assumed as main cause of deformations. However, in most of these cases we still think that earthquake is the most likely cause for the deformations observed. In 14 of the sites we do not see that any geological, sedimentary or other environmental conditions seem to favor other deformational mechanisms as likely as earthquake to have triggered the formation of the mosaic sand.

Table 1. Mosaic sand sites, thickness of mosaic sand, stratigraphic context, and possible, as well as most likely deformational mechanisms. ML= late-/postglacial marine limit.

Locality, m a.s.l., area, c. ML in m a.s.l.	**Mosaic sand thickness and stratigraphic context**	**Possible def. mechanisms**	**Most likely def. mechanisms**
1. Ånstad, Andørja, 25, southern Troms, 75	0.5 m in sublittoral sediments	A, E, F	A, F?
2. Skau, Bodø, 30, Nordland, 100	0.6 m in sublittoral sediments	A, E, F	A, F?
3. Bodø cemetery, 17, Nordland, 100	> 1 m in sublittoral sediments	A	A
4. Halsa, 50–70, Nordland, 100	> 2 m in sublittoral sediments	A	A
5. Reppen, 15, Nordland, 100	> 1.5 m in sublittoral sediments	A	A
6. Kila, 15, Nordland, 100	> 1 m in sublittoral sediments	A	A
7. Kila, 55, Nordland, 100	> 1.5 m in sublittoral sediments	A	A
8. Kila, 70, Nordland, 100	> 1 m in sublittoral sediments	A	A
9. Kila, 80, Nordland, 100	> 1.5 m in sublittoral sediments	A	A
10. Kila, 90, Nordland, 100	> 1 m in sublittoral sediments	A	A
11. Straumbotn, 38, Nordland, 110	> 1 m in sublittoral sediments	A, B, F	A, B?
12. Forsbakken, 80, Nordland, 110	0.5 m in deltaic sublittoral sed.	A, E, F	A, F?
13. Skille N, 30, Nordland, 120	> 1 m in sublittoral sediments	A, E, F	A
14. Skomo, 28, Nordland, 120	0.7 m in sublittoral sediments	A, E, F	A
15. Stormoen, 46, Nordland, 120	0.9 m in sublittoral sediments	A, E, F	A, F?
16. Dalbotnan, 80, Nordland, 120	>1 m in sublittoral sediments	A, E, F	A
17. Dalbotnan, 60, Nordland, 120	> 0.6 m in sublittoral sediments	A, E, F	A
18. Innvorda, 45, Trøndelag, 120	0.5 m in sublittoral sediments	A, E, F	A, F?
19. Klubbsteinen, 38, Trøndelag, 120	> 2.5 m in sublittoral sediments	A	A
20. Fonndalen, 77, Nordland, 100	> 1 m in sublittoral sediments	A, B	A
21. Grinder, 160, Brandval, Hedmark, 200	> 1 m in sublittoral sediments	A, B, C	A, B?

Deformational mechanism
A. Earthquake
B. Glaciotectonics
C. Landslide impact
D. Rock avalanche impact
E. Rapid sediment supply with gravity flow
F. Unspecified deformational mechanisms

Figure 30. Deformational structures in fine to medium deglacial sublittoral sand at Grinder (locality no. 21, Table 1), which resembles some of the structures in mosaic sand. It is, however, thought that glaciotectonics may have caused these deformations, in this case maybe more likely so than earthquake as deformational mechanism.

Conclusions

Deformational structures in sediments have various characters and causes, some are syn-genetic and formed during the sedimentary process, for instance those produced by extreme and rapid sediment supply, with or without gravity flows, others are post-genetic, like many glaciotectonic structures formed in older sediments. In this report we have focused on description of a special type of post-genetic deformational structures, which we describe as mosaic sand or 'ball and mosaic' sand, and which we think have been triggered and produced by strong earthquake. These structures are formed in originally deposited sublittoral layered fine to medium sand.

19–20 mosaic sand sites from the coastal part of northern and middle Norway, and one possible site from the inland of southern Norway have been recorded up to now. Two of these are described here, and photographs from some others are also included as examples of the variety of these structures.

The mosaic sand structures are developed during water-saturated conditions, from partial or less than full water-saturation with more angular character of the individual fragments of the mosaic (e.g., Klubbsteinen mosaic sand), to almost full or full water-saturation with rounded ball-like or drop-like fragments of the mosaic (e.g., Halsa mosaic sand).

Up to several meters thickness and several hundred meters of areal extension of the mosaic sand zones (e.g., at Halsa mosaic sand field) in originally layered shallow-marine fine to medium sand make other deformational mechanisms than earthquake, such as impact from landslides, rock avalanches, glaciotectonics, excess and rapid sediment supply with or without gravity flows, etc., much less likely or even unlikely to have caused the formation of the mosaic sands.

Water-saturation during formation of the mosaic sand makes it possible to estimate ages of the associated earthquakes by plotting mosaic sand elevations on a shore displacement curve, e.g. as indicated in Fig. 25.

Acknowledgements

All mosaic sand sites recorded in Norway, so far, have been observed and recognized since 1990 A.D. during general quaternary mapping by the Geological Survey of Norway. Two of the sites (Klubbsteinen and Halsa) have been used as excursion localities for both national and international students and researchers in quaternary geology since 1994 A.D. The general reaction from all visitors have been in unity: "This is unique, these structures deviates from all landslide, glaciotectonic, rapid sedimentation, gravity flow, or other commonly seen soft sediment deformations. This indicates a specific environment that requires homogeneous and unceasing impact of thick sand units, which most likely points to earthquake as the triggering factor". We agree, at least until somebody comes up with a record of similar structures in thick sand units where the deformational cause is clearly something else than earthquake. We also appreciate the record of the new mosaic sand site no. 20 (Fonndalen), which was first observed by two students, Heidi and Sunniva, University of Bergen, during fieldwork in August 2019.

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Appendix

Additional pictures from the Halsa mosaic sand field, and pictures from other mosaic sand localities in the vicinity. Pictures from some other mosaic sand localities further south along the Norwegian coast are included as well.

Figure A1. Pictures from the Halsa mosaic sand, old sand pit, top surface c. 54–55 m a.s.l. The close-ups show: to the right mosaic sand overlying sediments with various plastic as well as brittle deformation structures, and to the lower left: plastic deformation structures, like folds in originally layered sand.

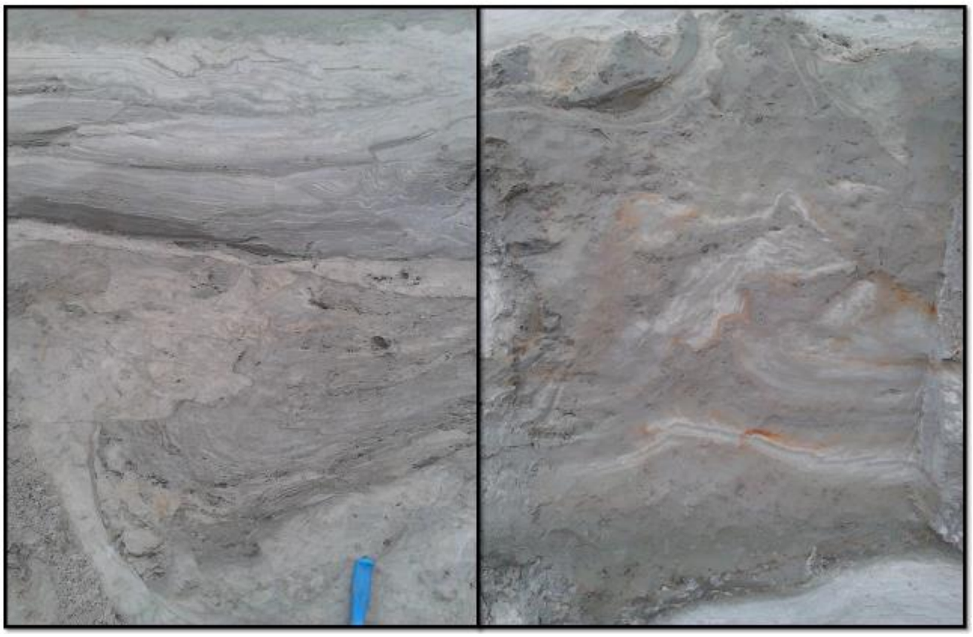

Figure A2. Various deformation structures in sands underlying mosaic sand in new sand pit at the Halsa mosaic sand field.

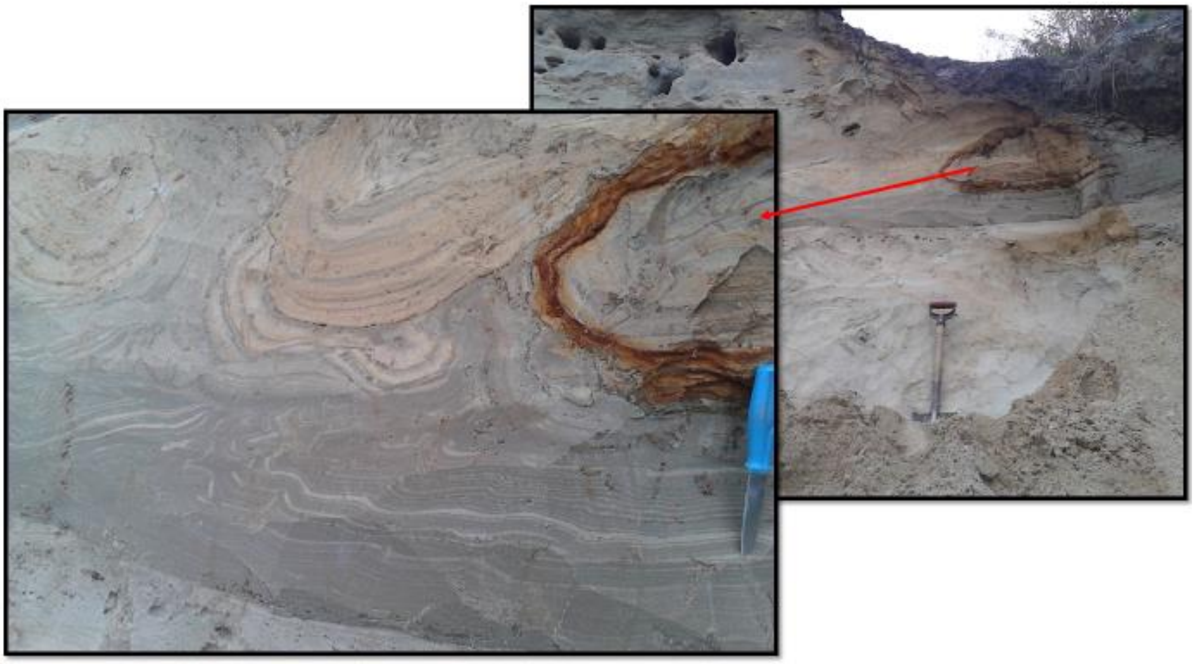

Figure A3. Folding and other deformation structures in sand underlying mosaic sand in the old sand pit at the Halsa mosaic sand field.

Figure A4. Localities with mosaic sand at the coast in Nordland County, southern part. Locality 6 is represented as loc. 15 in Table 1.

Figure A5. Mosaic sand in last deglaciation glaciofluvial shallow marine sediments in the Dalbotnan area, c. 80 m a.s.l., southern Nordland (loc. 4 in Fig. A4).

Figure A6. Mosaic sand from sub-littoral sand in the Dalbotnan area, c. 60 m a.s.l., southern Nordland (loc. 5 in Fig. A4). The mosaic sand is overlain by layered sand with various more elongated deformational structures.

Figure A7. Left: Mosaic sand c. 30 m a.s.l. north of Skille, southern Nordland (loc. 1 in Fig. A4). Right: Mosaic sand c. 30 m a.s.l. at Skomo, southern Nordland (loc. 2 in Fig. A4).

Figure A8. Mosaic sand like structures in units alternating with layered sand units hosting various elongated deformational structures (locality 3 in Fig. A4, not listed in Table 1).

Figure A9. Soft sediment deformations with folding in laminated clayey silt which underlies the sediment sequence with the mosaic sand like structures shown in Fig. A8.

Figure A10. Extra picture from the Klubbsteinen mosaic sand site (Figs. 26–27).

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